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PIXEL-WISE INTER/INTRA-CHANNEL COLOR & LUMINANCE UNIFORMITY CORRECTIONS FOR MULTI-CHANNEL PROJECTION DISPLAYS

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ABSTRACT

Inter- and intra-channel color and luminance are generally non-uniform in multi-channel projection display systems. Several methods have been proposed to correct for both inter- and intra-channel color and luminance variation in multi-channel systems in the past, with varying degrees of success. In this paper, a color and luminance correction method is proposed that alters the luminance and chromaticity of a projected image on an approximately pixel-wise basis by employing an imaging colorimeter. The final result is a pixel-wise gain mask, unique to each projector, which can be inserted into either the projection system or the image generator rendering pipeline to perform the required color calibration. This paper will describe the equipment, process, and algorithms required to perform such a correction using the Operational-Based Vision Assessment (OBVA) simulator as an example. Using this method, the 15-channel, 150-megapixel OBVA simulator display system is calibrated to uniform D65 and native white points, with uniform luminance, using luminance as the free parameter.

INTRODUCTION

Inter- and intra-channel color and luminance are generally non-uniform in multi-channel projection display systems. Intra-channel variations in luminance typically result in a higher luminance "hot spot" in the center of the projected image, while color uniformity can vary smoothly, but dramatically, across the full field of display. These problems are often compounded when using multi-channel systems, where color and luminance discrepancies are more easily observed near the "blend region," where adjacent images overlap to form a continuous image. Many methods have been proposed, and implemented, to correct for this color/luminance variation both within and between channels. Often, these methods are of the following form: The chromaticity is sampled in one or more locations for each channel where the red, green, and blue (RGB) input values are known; the chromaticity variation between sample locations are interpolated, and the corresponding RGB values are modified over this interpolated range to regularize the chromaticity. In general, the greater the number of sampled points, the greater the expected accuracy of the interpolated result [1, 2]. In this work we attempt to explore the limit of this method, in which each pixel is a sample point, ideally eliminating the chromaticity interpolation requirement and maximizing accuracy.

BACKGROUND

The color calibration procedure described herein was performed on the Operational-Based Vision Assessment (OBVA) flight simulator, which uses 15 Barco SIM10 projectors to produce an approximately 150-megapixel image over a 158° x 60° field of view (Figure 1). The blended image is viewed on a spherical, front projection screen (screen gain ≈0.88), with a 4-meter radius of curvature. The intended eye point of the observer is at the center of curvature, thus necessitating slightly off-axis projector locations. Each SIM10 projector is located approximately 6.8 to 7.3 meters from the projection surface, resulting in throw ratios of 2.8:1 to 3.1:1.

Figure 1: OBVA flight simulator display system.

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PIXEL-WISE SAMPLING

Color sampling typically makes use of a spectroradiometer or colorimeter capable of making spot measurements over a 2° or 10° field of view. However, in an attempt to maximize the number of sample points in this work, an imaging colorimeter has been used (Radiant Prometric, Model PM-1433F-1) with 3068x2044 native resolution. The candidate images, however, are produced using Barco SIM10 projectors, which exhibit 4096x2400 native resolution. Therefore, under the best case, the Radiant camera must undersample the projected image by a factor of approximately 0.64. However, to produce a valid colorimetric measurement, the colorimeter must be placed at the eye point of the intended observer, which is 4 meters from the display surface. Due to the available optics (Nikon Nikkor 20 mm, f/8), this geometry limits the number of useful colorimeter pixels to approximately 1400x900, which results in an overall down sampling factor of 0.128. Thus, roughly 8 display pixels are imaged to a single colorimeter pixel. Although this falls short of the goal of one sample per display pixel, it greatly exceeds any reasonable number of samples that could be obtained using a spot radiometer. For the remainder of this paper, it should be understood that the use of the word "pixel-wise" includes these limitations and, therefore, primarily refers to the usable pixels of the colorimeter, including the 8:1 down sampling factor. For the specific case of the SIM10 projector, for reasons which will be subsequently explained, the hardware implementation of any color correction necessarily requires a minimum of 4:1 down sampling, since the maximum size of the calibration mask is limited to 2048x1200 pixels.

CALIBRATION PROCEDURE

The pixel-wise calibration procedure used by the OBVA laboratory is detailed below. Although not all procedural steps are generally applicable to all projection systems, they are discussed in detail for completeness [3-7].

Step 1

For each projected channel, obtain full-field photographs via imaging colorimeter for each of the primary colors (RGB) at full luminance (Figure 2). For 8-bit color channels, full luminance for each channel is assumed to be a bit value, or digital count (i.e., d_r, d_g, d_b for red, green, and blue digital counts, respectively) of 255. Depending upon the nature of the projected image geometry, it will likely be necessary to de-warp the captured images to display a rectangular region of interest. This step is required to remove keystone effects due to non-coaxial placement of the camera and projector, or to remove radial warp (e.g., pincushion, barrel) introduced by cylindrical or spherical display surfaces [3, 4].

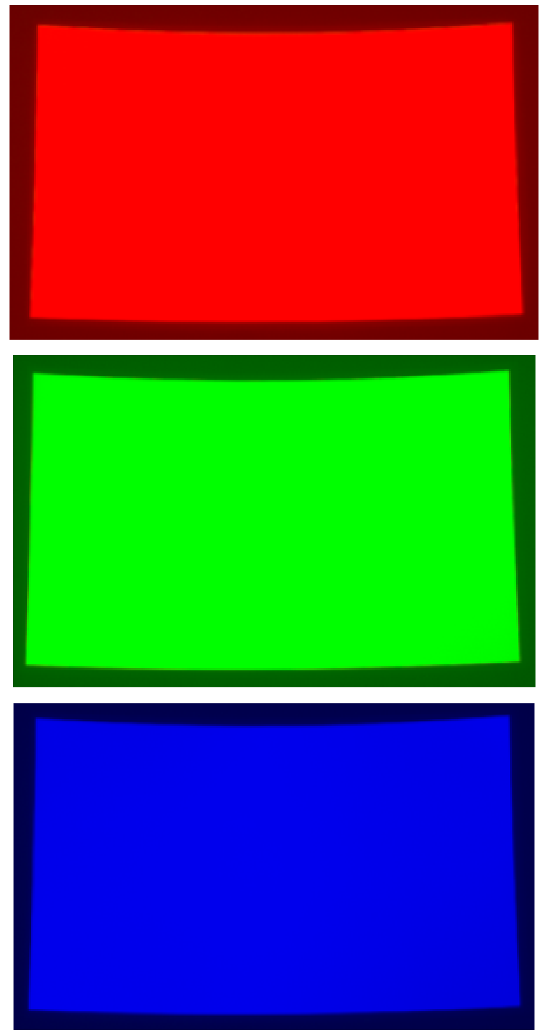


Figure 2: Red, green, and blue images captured via imaging colorimeter. Note that the spherical display and off-axis projector placement results in non-rectangular projection of each image.

In anticipation of this requirement, a fourth test pattern should be captured from the same camera location as the previous 3 color images. This test pattern should match the original projector aspect ratio and be suitable to perform image warping without introducing excessive error. For this work, a random grayscale checkerboard with a full-white border was generated in Matlab, as shown in Figure 3.

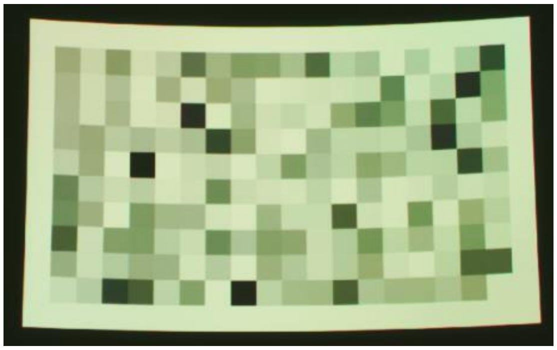


Figure 3: Random checkerboard test pattern. Note the high intensity border to facilitate edge detection.

The bright border allows unambiguous edge detection along the full perimeter, while the random intensity scale of each checker allows a more robust b-spline interpolation over the full pattern than a simple black/white checkerboard.

Step 2

Convert the photometer data to a usable format, as needed. In this work, the Radiant camera encodes each image as xyY chromaticity and luminance data, in a proprietary database format, which must first be converted to a Matlab datatype. Using the Radiant API, a dll was written to perform this conversion, resulting in a Matlab matrix containing the xyY data for each pixel in the image.

Step 3

The exact region of interest (ROI) must be determined by performing edge detection using the test pattern image. This same ROI is then applied to each of the RGB test images to remove the background and isolate the projected image. Then these images must be de-warped to recover the native rectangular aspect ratio (Figure 4). In this case, a non-rigid b-spline registration algorithm was applied to generate a 9x9 transformation matrix, which warps the recorded images to match the ideal random checkerboard pattern [8]. An equidistant 6x6 knot grid and 30 iterations were chosen, which yielded registration errors of approximately 1 pixel or less. In this case, the luminance of the reference checkerboard was biased by 2.5 cd/m^2 prior to image registration to account for the “integrating sphere effect” in the measured image.

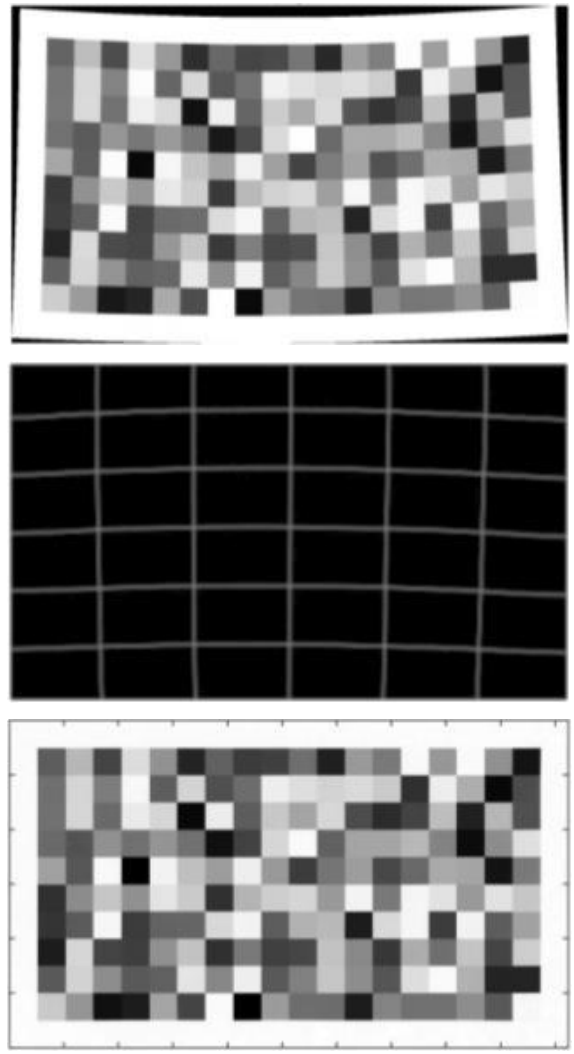


Figure 4: (top) Recorded image of the projected checkerboard, (middle) the corresponding warp mesh required to restore rectangular aspect to the recorded image, and (bottom) the de-warped checkerboard.

Both the ROI and transformation (warp) matrix found from the test pattern must be applied to the 3 color images, resulting in full field color images matching the original aspect ratio of the projector. The pre- and post-warp white images are shown in Figure 5 to illustrate the luminance nonuniformity. Note that the reuse of the same ROI and warp matrix requires that the imaging photometer remain stationary during each of the 4 image captures (RGB and test pattern). Any misalignment greater than ½ camera pixel between subsequent images will introduce excess error.

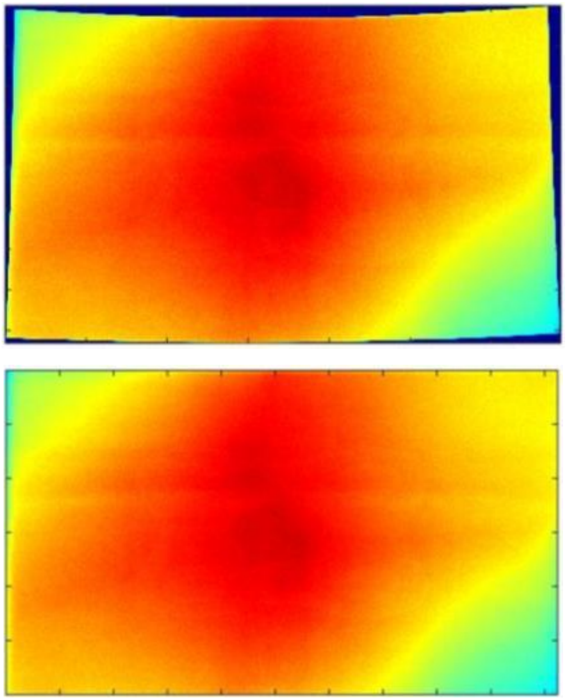


Figure 5: Pseudocolor luminance map of the native white image, both before (top) and after (bottom) image warping. The luminance image clearly exhibits a "hot spot" in the center and varies from a minimum (cyan) of $\mathbf{104.69}$ cd/m^2 to a maximum (red) of $\mathbf{149.91}$ cd/m^2.

Step 4

The xyY values of the native white image were measured at 9 points, in a 3x3 configuration across the full image field, to illustrate the initial state of the image as compared to the final state after uniformity correction (Figure 6). The mean chromaticity of the native white image was found to be:

$x = 0.3257 \pm 0.0035$,
$y = 0.3822 \pm 0.0024$,
$Y = 129.4 \pm 11.5$ cd/m^2.

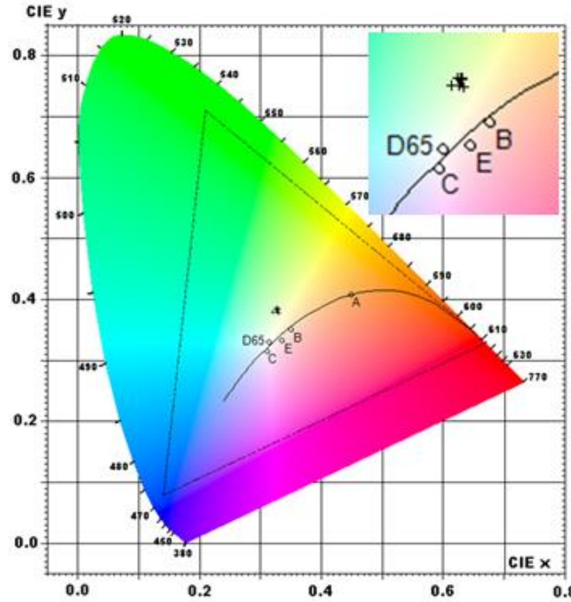


Figure 6: The *x,y* color coordinates of the native white image at 9 uniformly spaced points across the image field, with $\boldsymbol{x = 0.3257 \pm 0.0035}$, $\boldsymbol{y = 0.3822 \pm 0.0024}$, and $\boldsymbol{Y = 129.4 \pm 11.5}$ cd/m^2.

The XYZ color space is related to the xyY color space by the following relationships:

$$X = \left(\frac{x}{y}\right) \cdot Y, \tag{1}$$

$$Y = Y, \tag{2}$$

$$Z = \left(\frac{z}{y}\right) \cdot Y = \left(\frac{1-x-y}{y}\right) \cdot Y, \tag{3}$$

where *Y* is the luminance in cd/m^2 [6, 7]. The advantage of this color space is that each XYZ tristimulus value scales directly, and linearly, with the luminance. Thus, luminance may act as the free parameter, which may be reduced on a pixel-wise basis to match a common XYZ tristimulus values. The conversion to *x,y* values may be similarly performed as follows:

$$x = \frac{X}{X+Y+Z} \tag{4}$$

$$y = \frac{Y}{X+Y+Z} \tag{5}$$

Step 5

From the XYZ pixel values of each primary, the XYZ pixel values of the white image can be calculated, on a per pixel basis, by summing the individual tristimulus values of the red, green, and blue images:

$$XYZ_{native} = XYZ_r + XYZ_g + XYZ_b \quad (6)$$

In this work, it was noted that the chromaticity coordinates, *x,y*, of white pixels generated by the addition of independent color channels (as above) typically matched the *x,y* coordinates of measured white pixels to within a measurement error of ± 0.0005.

Step 6

Find the minimum X, Y, and Z pixel values within the white image for each projector. These X_{min}, Y_{min}, and Z_{min} values will determine the minimum limiting XYZ values necessary to equalize all pixels to form a uniform white over the full field of the projected image. Because these minimum pixel values cannot be increased (since the images are based upon full intensity of each color channel), the remaining pixels in the image (i.e., all pixels other than those at the minimum) must have their XYZ values reduced to match this minimum, as determined by the reduction in luminance, Y. This pixel-wise reduction will subsequently bring all remaining pixels to a common white point, denoted as XYZ_{common}. It should be noted that in general the minimum X, Y, and Z pixel values will not occur at the *same* pixel location. Thus, there will generally be a pixel with minimum X, another with minimum Y, and a third exhibiting the minimum Z value. These XYZ_{min} values are used in equations 4 & 5 to determine the new *x,y* chromaticity value of the common white point. In this example, the initial intra-projector pixel luminance varied from $Y_{max} = 104.69$ cd/m^2 to $Y_{max} = 149.91$ cd/m^2. As expected, the dimmest pixel's maximum luminance set the constraint on the brightest "common" minimum white point, which was found to be:

$$XYZ'_{cw} = [90.86 \quad 104.69 \quad 78.73]' \quad (7)$$

If D65 is the desired white point, then the D65 chromaticity coordinates, $x_{D65} = 0.31271, y_{D65} = 0.32902$, must be used in equations 1-3 while the luminance is varied to match the XYZ_{min} values. In this work, the Y value was iteratively reduced in small increments, while *x,y* was continually recalculated, to determine the necessary values to generate XYZ_{D65}. It should be noted that this is typically, but not always, possible, and in some cases the primary color channels may support a common minimum white point with XYZ values below those required for a D65 white point. In this example, the tristimulus values required to generate uniform D65 white (chromaticity $x_{D65} = 0.31271, y_{D65} = 0.32902$) were found to be:

$$XYZ'_{D65} = [68.72 \quad 72.30 \quad 78.73]' \quad (8)$$

where the maximum luminance to support these values was found to be $Y_{D65} = 72.30$ cd/m^2, a reduction of over 30% from that of the brightest "common" white point. At this point, the necessary XYZ chromaticity values have been fully determined for intra-channel color correction. However, for multi-channel projection systems, the XYZ tristimulus values for the desired white point (D65 or otherwise) must be determined for each projector until the global minimum Y_{D65} is found. The calculations for each projector must then be repeated using this new global minimum as the most strict luminance constraint upon each projector within system. After performing identical measurements on all 15 projectors, the global minimum luminance to generate uniform D65 white over all 15 channels was found to be $Y_{D65} = 50.60$ cd/m^2, resulting in the following tristimulus values for this projector:

$$XYZ'_{D65} = [48.09 \quad 50.60 \quad 55.10]' \quad (9)$$

Note that global uniformity requires the luminance of this projector to be reduced by 51.6% from that of the best "common" intra-projector white, and it is two-thirds lower than the brightest possible pixel of the initial state.

Step 7

The pixel-wise XYZ tristimulus values must be converted to RGB values, which describe the digital color space of the projector, using a pixel-wise monitor matrix. The monitor matrix is based upon each pixel's measured XYZ values, with the relationship between RGB and XYZ holding true for each pixel, such that:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (10)$$

where $X, Y, Z_{r,g,b}$ are the pixel-wise tristimulus values of the red, green, and blue images recorded at full intensity (d_r, d_g, d_b = 255) [6, 7]. The central 3x3 matrix is traditionally referred to as the "monitor matrix" *M*. Assuming an inverse exists for *M*, the new RGB_{D65} values can be determined by:

$$\begin{bmatrix} R_{D65} \\ G_{D65} \\ B_{D65} \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix}^{-1} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} \quad (11)$$

where XYZ_{D65} denote the desired tristimulus values to generate a D65 white point. Since these RGB values represent the maximum luminance at which each primary color may be displayed before violating the D65 constraint, all but the limiting pixels must necessarily scale over a reduced range, from 0 to less than 255, often much less depending on the constraint of the white point.

Step 8

If necessary, perform a γ (gamma) correction on the RGB values. For projectors or image generators that implement a γ correction, the RGB values will need to be modified accordingly. In this work no γ correction was necessary since these pixel-wise corrections operate on an approximately linear basis within the Sim10 projector. This was verified by spot checking the luminance against several alpha values, as shown in Figure 7. However, it should be noted that the gamma correction is often nothing more than a look-up table. Therefore, if the γ curve of the display has been carefully measured, it may be possible to more accurately correct the data using a general polynomial fit. It should further be noted that, for maximal accuracy, the γ correction should also be performed on a pixel-wise basis, which would require the full γ curve to be characterized using an imaging photometer (which was not done in this work). For the sake of completeness, the γ correction would be of the form:

$$R, G, B = \left[\kappa_{G,r,g,b} \left(\frac{d_{r,g,b}}{255}\right) + \kappa_{O,r,g,b}\right]^{\gamma_{r,g,b}} \qquad (12)$$

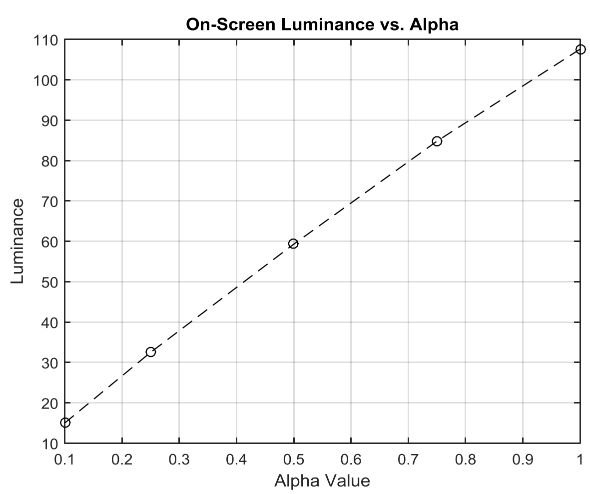


Figure 7: Measured linear relationship between α and luminance.

where κ_G and κ_O represent the amplification (gain) and bias (offset), respectively, of each red, green, and blue color channel, and γ is an empirically determined (or assumed) parameter [6, 7]. Having calculated the necessary RGB_{D65} values from equation 11, the necessary digital counts can be found by solving equation 12 for the desired $d_{r,g,b}$ value.

Step 9

The resulting RGB values are used to modify the displayed primary colors, on a pixel-wise basis. In this work, the resulting RGB values were scaled between 0 and 1. Because the resulting RGB values are maximum common values, for which the native bit values must be reduced, this scaled RGB matrix represents the pixel-wise multiplication factor, which must be applied to each color to maintain color uniformity. In this work, we were able to generate a 3-layer tiff file containing these values, to be used as a multiplicative α (alpha) mask. The RGB values of each frame of the rendered image are subsequently multiplied by this α mask to maintain color uniformity throughout the simulated scenario. In this work, the α mask was able to reside directly within the Sim10 projector, effectively placing it at the final stage of the rendering pipeline, which is where this mask would reside if implemented in the image generator.

Figure 8: (top) The α mask necessary to bring the projector to a uniform "common" white, and (bottom), the α mask necessary to bring the projector to a uniform D65 white.

Note that the α mask required for the best "common" white point (Figure 8, top) exhibits the brightest pixels near the lower right corner, which is expected, since this is where the initial luminance was lowest (from Figure 5), with the lowest luminance pixels generally setting the limiting constraint. All other pixels must be reduced to a greater degree. The nature of the color correction can also be seen directly in the α mask, via its color variation. The upper right corner of the recorded image was slightly greenish ($x = 0.3225, y = 0.3845$); thus, we expect this corner of the α mask to tend toward magenta for correction. Similarly, the upper left corner of the recorded image was slightly red ($x = 0.3292, y = 0.3778$); thus, the α mask is expected to tend toward the blue/green in this region. The α mask for D65 correction (Figure 8, bottom) exhibits these same qualities, although the most salient characteristic here is the great reduction in luminance to reach D65, which is dictated by the global minimum. To reach D65, this mask must move the white point significantly toward the blue. The chromaticity coordinates of the native and corrected white images were measured to be:

$$x_{native} = 0.3257 \pm 0.0035$$
$$y_{native} = 0.3822 \pm 0.0024$$
$$Y_{native} = 129.4 \pm 11.5 \text{ cd/m}^2$$

$$x_{cw} = 0.3317 \pm 0.0012$$
$$y_{cw} = 0.3809 \pm 0.0012$$
$$Y_{cw} = 109.1 \pm 1.4 \text{ cd/m}^2$$

$$x_{D65} = 0.3162 \pm 0.0019$$
$$y_{D65} = 0.3310 \pm 0.0025$$
$$Y_{D65} = 57.8 \pm 0.6 \text{ cd/m}^2$$

as shown in Figure 9. It is noteworthy that the "common" white chromaticity, as expected, did not change significantly from the "native" white of the projector, since all of the corrected pixels were simply brought to match the least bright white native pixel. However, this correction reduced the standard deviation of x,y by approximately 50%, resulting in more uniform color. The D65 correction moved the entire white point, at great cost to luminance, to x, y_{D65}, while also reducing standard deviation, albeit to a lesser degree.

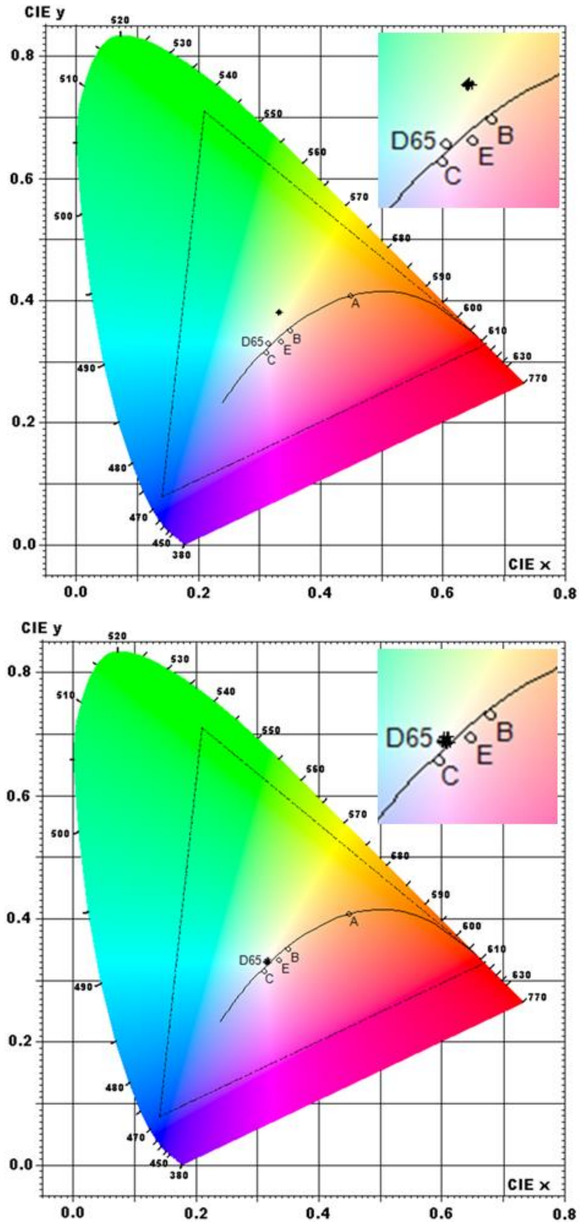
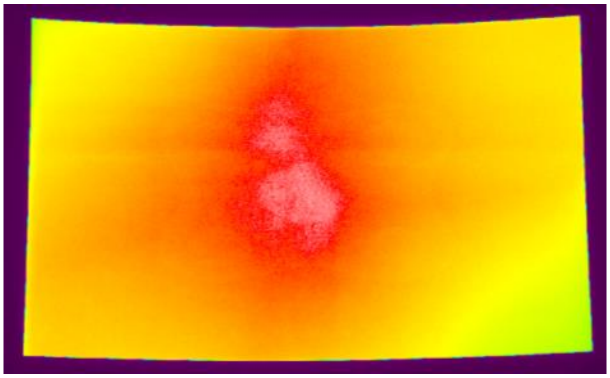


Figure 9: (top) *x,y* chromaticity coordinates for the best "common" white point, and (bottom)the *x,y* chromaticity coordinates for the D65 white point.

Figure 10 reveals that the luminance uniformity has been greatly improved as well. The initial luminance standard deviation was approximately 10%, while the corrected luminance variation for both the "common" and D65 white images is on the order of 1%.



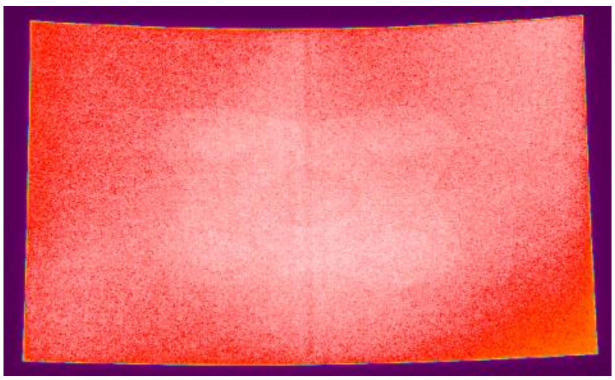


Figure 10: (top) Luminance profile prior to correction, ranging from a minimum (green) of 104.69 cd/m^2 to a maximum (white) of 149.91 cd/m^2, and (bottom) the D65 corrected luminance profile, ranging from a minimum (orange) of 55.2 cd/m^2 to a maximum (white) of 59.0 cd/m^2.

CONCLUSION

A method has been presented to correct color and luminance non-uniformity in single and multi-channel projection systems that uses an imaging colorimeter to maximize the number of sample points. This maximization of sample points can generally be extended to include pixel-wise sampling and color correction to eliminate the need for color interpolation between samples. Several practical considerations have been examined, including the requirement to de-warp the measured image prior to calculating the color correction, as well as verification on an operational display system.

Process Summary

1. Obtain imaging colorimeter photographs
    a. Red, green, blue images at maximum luminance
    b. Random checkerboard, or other suitable image, for de-warping
    c. Full white image, for before/after comparison (if desired)
2. Convert colorimeter data to Matlab format (as needed)
3. De-warp each image to the original rectangular aspect
4. Convert xyY chromaticity to XYZ tristimulus values for each color channel
5. Establish the desired white point
6. Find minimum tristimulus values for white (with luminance as a free parameter)
    a. Higher tristimulus values get cut down to this minimum
    b. For multi-projector systems, find the global minimum and repeat step 6 for each channel
7. Convert the new XYZ values to the projector's RGB color space using pixel-wise monitor matrix
8. Perform gamma correction (as needed)
    a. Not needed for the Sim10 used in this work
9. The result is 3-layer multiplicative (gain) RGB mask containing values from 0 to 1 for each color
    a. Insert gain mask into the projector or final stage of the rendering pipeline

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